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(54) Apparatus and method of induction logging

(57) Apparatus and method are disclosed for determining properties of subsurface formations surrounding a bore-hole by induction logging. The properties which can be determined include the formation dip angle and dip azimuth angle. Indications of formation anisotropy can also be obtained. An array of individually energizable transmitter coils is provided, preferably including three coils having mutually orthogonal axes. Electronic transmitter steering circuitry is provided for controlling the energizing means to electronically steer the direction of the magnetic moment resulting from the magnetic field components generated by the transmitter coils. An array of receiver coils is also provided along with receiver processing circuitry for processing signals induced in the receiver coils. The array of receiver coils preferably includes three receiver coils having mutually orthogonal axes. The receiver processing circuitry is capable of individually sensing the signals induced in the receiver coils and operates to combine the sensed signals. The receiver processing circuitry also includes electronic receiver steering circuitry for controlling the relative amplification of the sensed signals to steer the effective sensing direction of the receiver. The receiver steering circuitry is coordinated with the transmitter steering circuitry and is operative to rotate the effective sensing direction of the receiver in a plane perpendicular to the direction of the transmitter magnetic moment.

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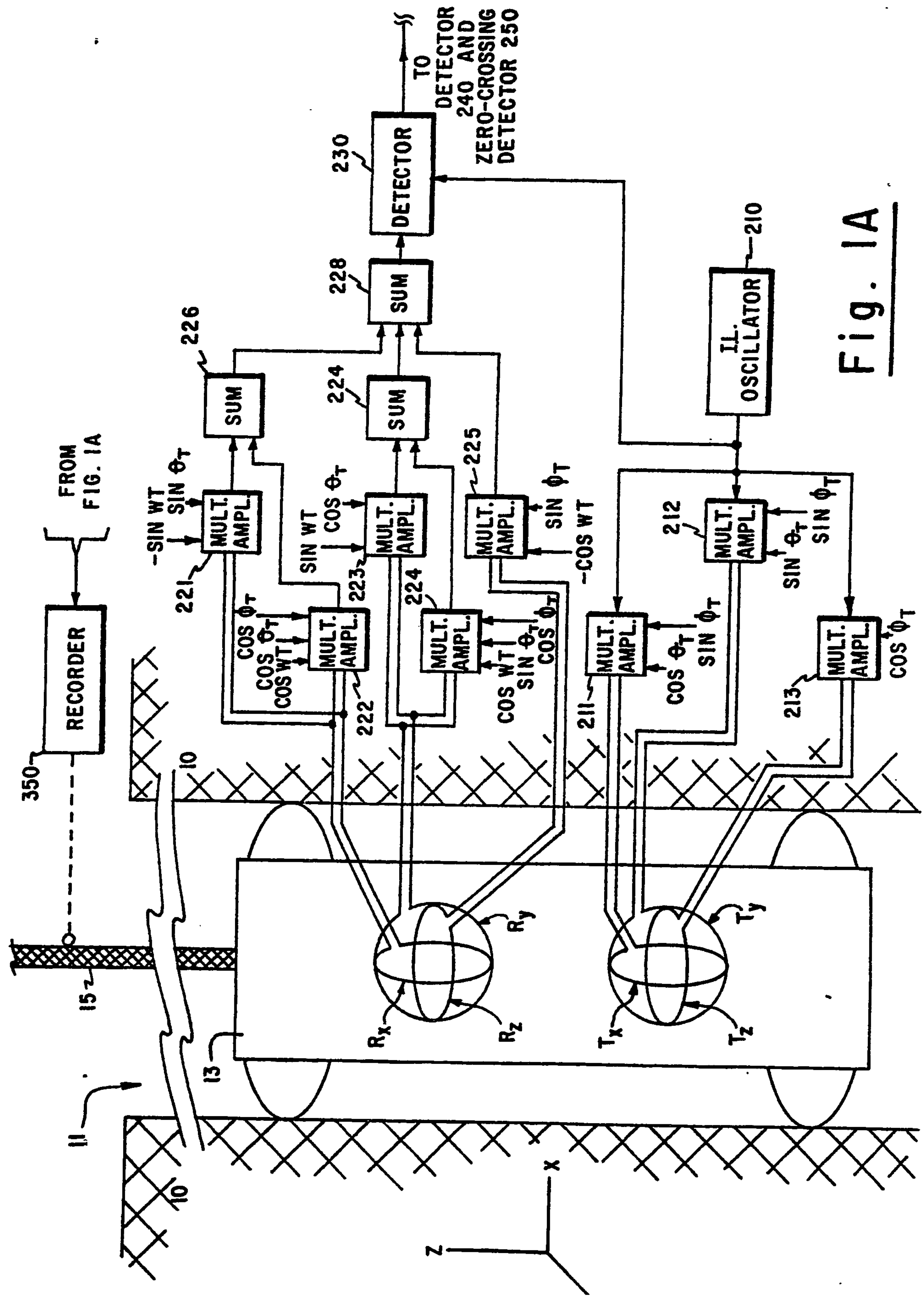
TO DETECTOR 240 AND ZERO-CROSSING DETECTOR 250
230
DETECTOR
228
SUM
226
SUM
224
SUM
210
I.L. OSCILLATOR
FROM FIG. IA
-SIN WT
SIN ϕ_T
MULT. AMPL.
221
SIN WT
COS ϕ_T
MULT. AMPL.
223
225
MULT. AMPL.
SIN ϕ_T
-COS WT
212
MULT. AMPL.
SIN ϕ_T
SIN ϕ_T
COS ϕ_T
COS ϕ_T
COS WT
MULT. AMPL.
222
224
MULT. AMPL.
COS WT
SIN ϕ_T
COS ϕ_T
MULT. AMPL.
211
COS ϕ_T
SIN ϕ_T
MULT. AMPL.
213
COS ϕ_T
RECORDER
350
10
15
13
11
10
R_y
R_x
R_z
T_y
T_x
T_z
X
Z

Fig. 1A

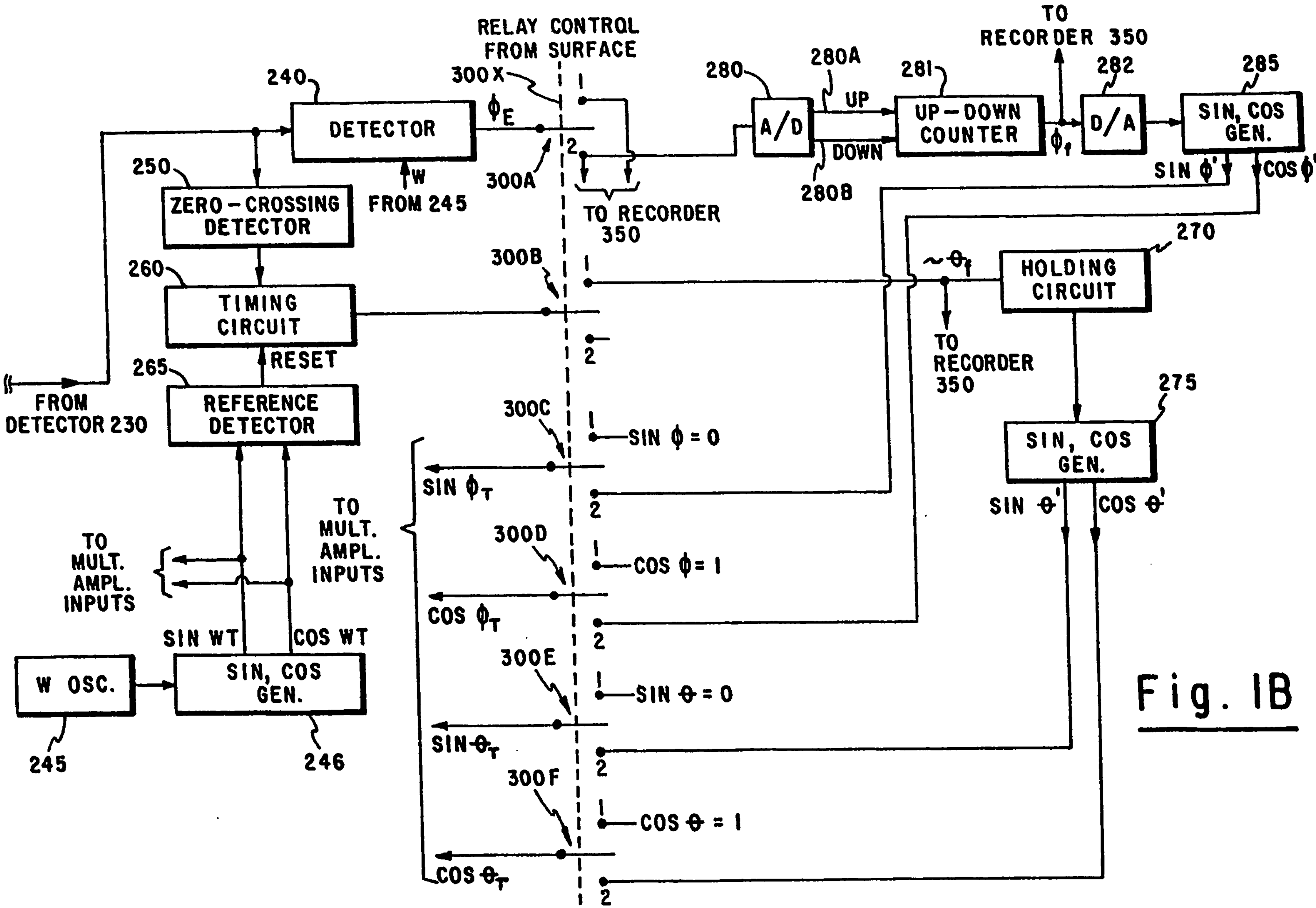

Fig. 1B

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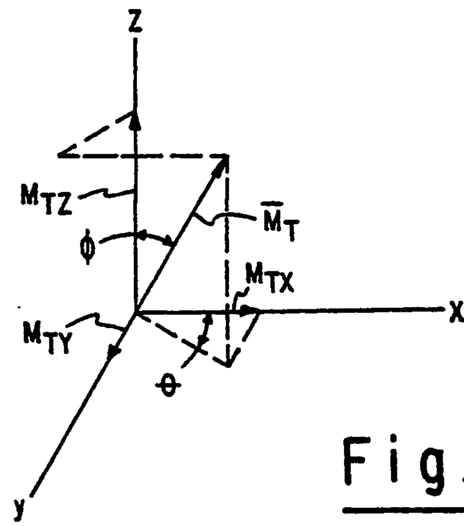
Z
M_{TZ}
$\bar{M}_T$
ϕ
M_{TX}
X
M_{TY}
θ
y

Fig. 2

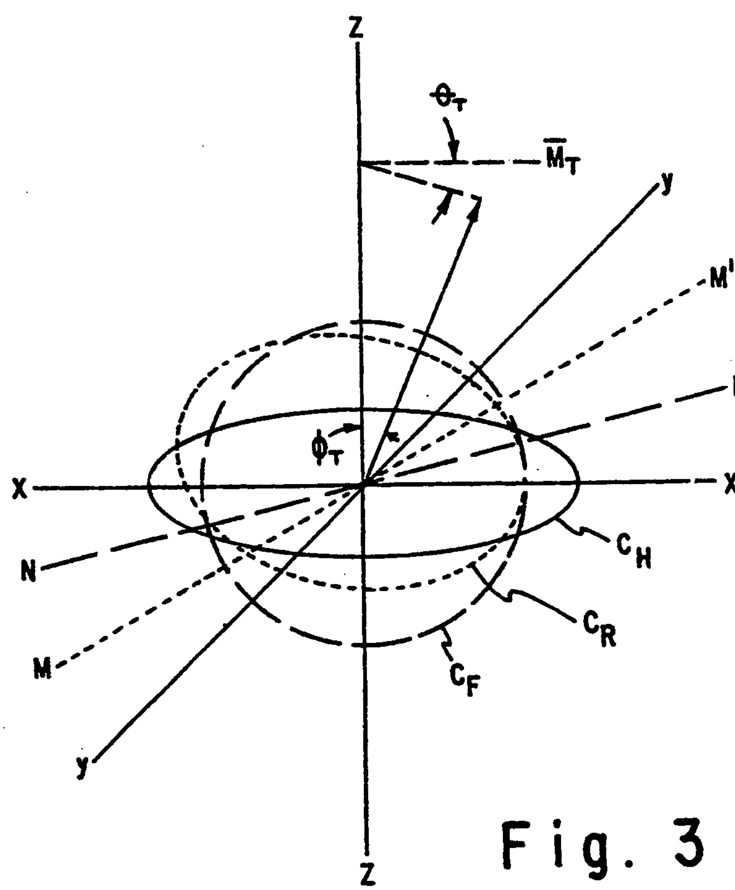
Z
θ_T
$\bar{M}_T$
y
M'
N'
ϕ_T
X
X
C_H
N
C_R
M
C_F
y
Z

Fig. 3

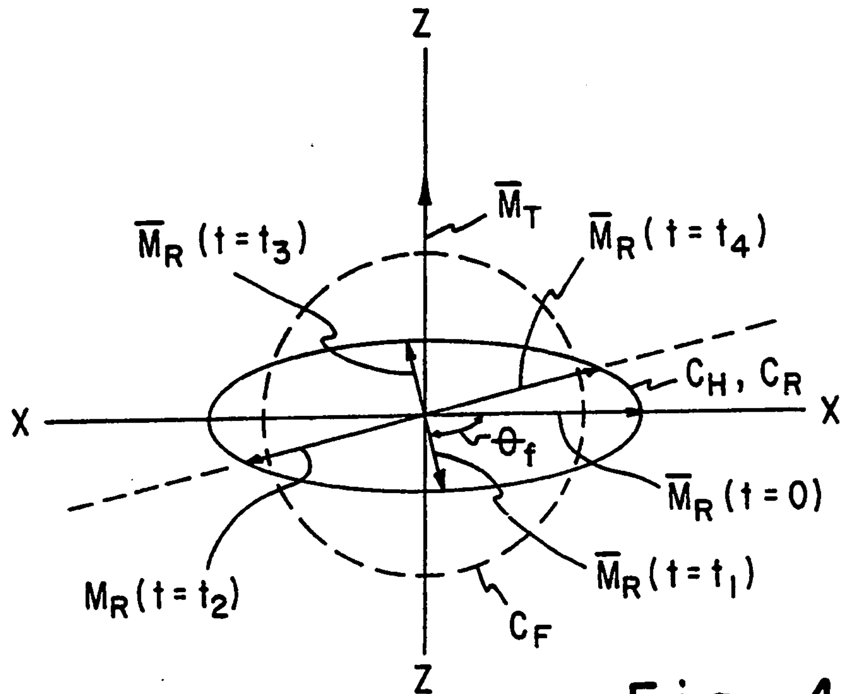
Z
$\overline{M}_T$
$\overline{M}_R$ (t = t_3)
$\overline{M}_R$ (t = t_4)
C_H, C_R
X
X
θ_f
$\overline{M}_R$ (t = 0)
M_R (t = t_2)
$\overline{M}_R$ (t = t_1)
C_F
Z

Fig. 4

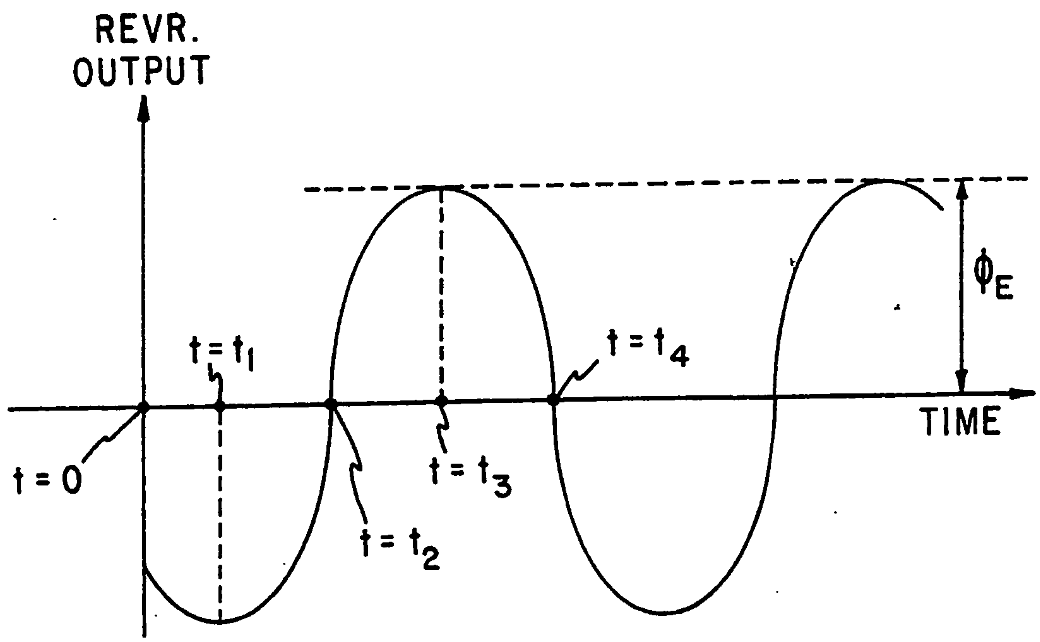
REVR.
OUTPUT
ϕ_E
t = t_1
t = t_4
TIME
t = 0
t = t_3
t = t_2

Fig. 5

SPECIFICATION

Apparatus and method of induction logging

Technical Field

This invention relates to an apparatus and method for determining properties of subsurface formations surrounding a borehole. The properties which can be determined include the dip angle and dip azimuth angle of anisotropic formation beds. The invention has particular utility in determining the presence and orientation of fractures, and is especially useful in open boreholes or in boreholes filled with a drilling fluid that is relatively nonconductive as compared to the formations being logged.

Background Art

It is common practice to obtain measurements of the dip angle and azumuthal angle (also called the dip azimuth angle) of formation bedding planes by passing through an earth borehole a "dipmeter" tool having a plurality of circumferentially spaced pad mounted electrodes. Survey current is emitted from certain ones of the electrodes on each pad member to obtain a measure of the resistivity or conductivity of the adjoining earth formations to produce a plurality of resistivity logs. By properly correlating the fluctuations of these resistivity logs, the positioning of a bedding plane relative to the tool position can be readily calculated. Then, by measuring the bearing of the tool-relative to some azimuthal reference, such as magnetic north, and the inclination of the tool relative to the true vertical or gravitational axis, the position of a bedding plane relative to the north and true vertical axes can be determined.

While conventional multiple pad dipmeter devices have provided generally satisfactory results, there are some difficulties inherent in these devices. For example, it is generally necessary to perform accurate correlations of a number of signals. Further, if the borehole is open-hole or filled with a relatively non-conductive drilling mud, such as an oil base drilling mud, the pad mounted electrodes need to make reasonably good contact with the formations surrounding the borehole in order to be assured of valid measurements.

Another type of dipmeter device that has been proposed is the so-called "induction dipmeter" which uses principles of induction logging to measure dip. Conventional induction logging employs coils wound on an insulating mandrel. One or more transmitter coils are energized by an alternating current. The oscillating magnetic field produced by this arrangement results in the induction of currents in the formations which are nearly proportional to its conductivity. These currents, in turn, contribute to the voltage induced in receiver coils. By selecting only that voltage component which is in-phase with the transmitter current, a signal is obtained that is approximately proportional to the formation conductivity. The transmitting coils of a conventional induction logging apparatus tend to induce secondary current loops in the formations which are concentric with the transmitting and receiving coils. However, certain conditions of the surrounding earth formations, such as dipping beds or fractures, can cause the average plane of these secondary current loops to vary from a concentric alignment. Induction dipmeters attempt to use this phenomenon to advantage by measuring the voltages induced in coils having different orientations. In one type of prior art induction dipmeter scheme, a coil array is mechanically rotated at a constant frequency to produce modulation components in receiver coil signals at the frequency of rotation of the coil array. These modulation components are processed to obtain indications of the dip and/or dip azimuth of formation bedding planes. A disadvantage of this type of induction dipmeter is the requirement for bulky and power consuming equipment for rotating the coil array and for keeping track of the orientation of the coil array as it rotates. Accordingly, mechanically rotating induction dipmeters have not achieved significant commercial acceptance. Examples of mechanically rotating induction devices can be found in U.S. Patent Nos. 3,014,177, 3,187,252, and 3,561,007.

In addition to schemes which utilize mechanically rotating coils, prior art proposals have also been set forth for utilizing mechanically passive induction coils to obtain measurements of formation dip and/or anisotropy. For example, in the U.S. Patent No. 3,510,757, vertical (i.e., aligned with the borehole axis) transmitter coils are used in conjunction with a pair of orthogonal, horizontal (i.e., perpendicular to the borehole axis) receiver coils. The outputs of the receiver coils are recorded and utilized to obtain indications of formation dip angle. In the U.S. Patent No. 3,808,520, a vertical transmitter coil is used in conjunction with three receiver coils having mutually orthogonal axes; i.e., one vertical and two mutually orthogonal horizontal coils. The outputs of the three receiver coils are utilized in specified relationships to obtain combined dip and anisotropy information.

It is among the objects of the present invention to provide an induction logging technique for obtaining dip and/or anisotropy information, and which is particularly effective in situations where the formations being logged are much more highly conductive than the borehole medium in which a logging device is disposed.

Summary of the Invention

energy into said formations by individually energizing transmitter coils in a transmitter coil array and electronically steering the direction of the magnetic moment resulting from the magnetic field components generated by said transmitter coils; and processing signals detected in receiver coils of a receiver coil array to derive said properties.

Another aspect of the present invention is directed to an apparatus for determining properties of subsurface formations surrounding a borehole, comprising: an array of transmitter coils; an array of receiver coils; means for individually energizing said transmitter coils; electronic transmitter steering means for controlling said energizing means to electronically steer the direction of the magnetic moment resulting from the magnetic field components generated by said transmitter coils; and receiver processing means for processing the signals induced in said receiver coils.

Further features and advantages of the invention will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings.

Brief Description of Drawings

FIG. 1, consisting of FIGS. 1A and 1B placed side-by-side, illustrates an embodiment of the invention in a borehole, along with a schematic representation, partially in block form, of the coil arrays and associated circuitry.

FIG. 2 illustrates the transmitter magnetic moment unit vector and its components.

FIG. 3 is useful in understanding geometric relationships relating to the invention.

FIG. 4 illustrates geometric relationships relating to the beginning of a measuring sequence in accordance with an embodiment of the invention.

FIG. 5 illustrates the typical receiver output signal waveform that is processed in accordance with the invention.

Preferred Mode For Carrying Out The Invention

Referring to FIG. 1, there is shown a representative embodiment of an induction logging apparatus in accordance with the present invention for investigating earth formations 10 traversed by a borehole 11. It is preferred that the invention be employed in situations where the borehole is either filled with a drilling fluid that is relatively nonconductive as compared to the formations being logged, or is empty hole. The downhole device of the logging apparatus includes coils mounted on a centralized support member 13 adapted for movement through the borehole 11. The downhole device also includes a fluid-tight enclosure which contains electronic circuitry, this circuitry being shown in block diagram form at the side of the borehole. The downhole device is suspended from the surface of the earth by an armored multiconductor cable 15. A suitable drum and winch mechanism (not shown) is located at the surface of the earth for raising and lowering the device through the borehole. Also located at the surface of the earth may be a power supply (not shown) for supplying electrical energy by way of the cable 15 to the downhole equipment.

The downhole device includes an array of transmitter coils having mutually orthogonal axes and designated T_x, T_y and T_z, and an array of receiver coils having mutually orthogonal axes and designated R_x, R_y and R_z. In the present embodiment, the transmitter coil T_z and the receiver coil R_z have their axes aligned with the borehole axis; i.e., the z direction in FIG. 1. The transmitter coil T_x and the receiver coil R_x have their axes aligned perpendicular to the borehole axis and in the x direction in FIG. 1. The transmitter coil T_y and the receiver coil R_y have their axes perpendicular to both the borehole axis and perpendicular to the x direction; i.e., in the y direction in FIG. 1. (For ease of explanation, the logging device is assumed to be aligned with the z axis in a vertical borehole. Coordinate corrections can be implimented, in known manner, using signals from a compass and an inclinometer). The transmitter coils preferably, although not necessary, have intersecting axes and may be concentric, as shown. The same is true of the receiver coils. The transmitter-to-receiver spacing is preferably, although not necessarily, quite short, for example, of the order of one foot or less. In fact, the transmitter and receiver may, if desired, be at substantially the same location.

As described briefly above, an aspect of the invention involves electronically steering the direction of the magnetic moment resulting from the magnetic field components generated by the transmitter coils. A further aspect of the invention involves "steering" at the receiver by controlling the relative sensitivities of sensing means that are coupled to the receiver coils. Before describing the circuitry utilized to implement these functions, some theoretical considerations shall be set forth.

A small induction logging coil carrying a current can be represented as a magnetic dipole having a magnetic moment proportional to the current. The direction and strength of magnetic moment can be represented by a vector perpendicular to the plane of the coil. Three such coils with mutually perpendicular axes (such as the transmitter coils in FIG. 1) can be represented by three corresponding magnetic moment vectors. By combining mutually perpendicular vectors of appropriate magnitudes, one can obtain a resultant magnetic moment vector designated $\overline{M}_T$, in any desired direction and magnitude. Thus, by passing currents of appropriate relative magnitudes through three mutually perpendicular coils, one can obtain a magnetic field that is theoretically equivalent to the magnetic field of a single coil with any desired orientation. Reference is made, for example, to FIG. 2 which illustrates magnetic moments designated M_{TX}, M_{TY}, and M_{TZ}, and a resultant magnetic moment $\overline{M}_T$, which is at a

(tilt) angle ϕ with respect to the z axis and which has a projection on the xy plane at an (azimuthal) angle θ.

Directionality can also be attributed to the receiver, as follows: If the sensitivities (or amplification factors) of the circuits coupled to individual receiver coils are appropriately selected, the resultant of the signals induced in the three mutually orthogonal coils can be "steered" to any desired direction. For example, one could consider each of the receiver coils as having a coil moment represented as a vector. The magnitude of the coil moment for each individual coil is proportional to the product of the number of turns times the cross-sectional area of the turns times the adjustable sensitivity (or amplification) attributable to the coil. A receiver coil moment vector, $\overline{M}_R$, can be considered as being made up of the sum of three coil mement components designated M_{RX}, M_{RY}, and M_{RZ}, which correspond to the contributions from three coils having axes in the x, y, and z directions.

The transmitter vector $\overline{M}_T$ illustrated in FIG. 2, can be expressed in vector notation in terms of the angles ϕ and θ at the transmitter, these angles being designated as ϕ_T and θ_T, respectively. The expression for $\overline{M}_T$ is:

$$\overline{M}_T = M_T\,[\overline{i}\cos\theta_T\sin\phi_T + \overline{j}\sin\theta_T\sin\phi_T + \overline{k}\cos\phi_T] \qquad (1)$$

where M_T is an amplitude constant and $\overline{i}$, $\overline{j}$ and $\overline{k}$ are unit vectors in the x, y and z directions, respectively. The angles ϕ_T and θ_T can be visualized as defining the orientation of the resultant transmitter magnetic moment vector, $\overline{M}_T$. Stated another way, to achieve a vector orientation (ϕ_T, θ_T), the currents supplied to the transmitter coils of FIG. 1 should be in accordance with the following Table I (assuming the coils have the same number of turns):

Table I

coil	current proportional to:
T_x	$\cos\theta_T\sin\phi_T$
T_y	$\sin\theta_T\sin\phi_T$
T_z	$\cos\phi_T$

Now, consider the following expression for a receiver coil moment vector, $\overline{M}_R$:

$$\begin{aligned}\overline{M}_R = M_R\ [&\overline{i}(-\sin\omega t\sin\theta_T + \cos\omega t\cos\theta_T\cos\phi_T)\\ &+\overline{j}(\sin\omega t\cos\theta_T + \cos\omega t\sin\theta_T\cos\phi_T)\\ &-\overline{k}\cos\omega t\sin\phi_T]\end{aligned} \qquad (2)$$

where M_R is an amplitude constant. It can be verified that this receiver coil moment vector is perpendicular to the transmitter magnetic moment vector $\overline{M}_T$, and that it rotates around $\overline{M}_T$ at an angular frequency ω. For example, if one takes the scalar product $\overline{M}_T \cdot \overline{M}_R$, it is zero for all values of ω. This can be seen by multiplying the $\overline{i}$ terms, the $\overline{j}$ terms, and the $\overline{k}$ terms to obtain the following products:

product of $\overline{i}$ terms:
$\cos\theta_T\sin\phi_T(-\sin\omega t\sin\theta_T + \cos\omega t\cos\theta_T\cos\phi_T) = -\cos\theta_T\sin\theta_T\sin\phi_T\sin\omega t + \cos^2\theta_T\sin\phi_T\cos\phi_T\cos\omega t$

product of $\overline{j}$ terms:
$\sin\theta_T\sin\phi_T(\sin\omega t\cos\theta_T + \cos\omega t\sin\theta_T\cos\phi_T) = \cos\theta_T\sin\theta_T\sin\phi_T\sin\omega t + \sin^2\theta_T\sin\phi_T\cos\phi_T\cos\omega t$

product of $\overline{k}$ terms:
$-\cos\phi_T(\cos\omega t\sin\phi_T) = -\cos\phi_T\sin\phi_T\cos\omega t$

When these terms are added together, the result is zero. In particular, the first terms of $\overline{i}$ and $\overline{j}$ products cancel. The sum of the second terms of the i and j products cancel with the single $\overline{k}$ product term. Thus, the following Table II, sets forth the relative sensitivities (or amplification factors) for the respective receivers which produces an effective resultant receiver coil moment that is perpendicular to the transmitter coil magnetic moment M_T, and rotates in the plane perpendicular to $\overline{M}_T$ at an angular frequency ω:

Table II

coil	receiver amplification
R_x	$-\sin\omega t\sin\theta_T + \cos\omega t\cos\theta_T\cos\phi_T$
R_y	$\sin\omega t\cos\theta_T + \cos\omega t\sin\theta_T\cos\phi_T$
R_z	$-\cos\omega t\sin\phi_T$

In Table II, it is assumed that each coil has the same cross-sectional area and number of turns, so the factors set forth can be implemented by providing appropriate relative amplification to amplifiers that are used in conjunction with the individual receiver coils.

In accordance with the preferred form of the invention, the resultant of the receiver coil moments (collectively referred to as the receiver vector $\overline{M}_R$) is caused to rotate around the transmitter vector $\overline{M}_T$, and a generally sinusoidally varying signal will usually be obtained at the receiver output. As will be explained further hereinbelow, the amplitude of the receiver output signal will depend upon the dip angle and degree of anisotropy of the surrounding formations. The relative phase of the receiver output signal will be a function of the dip azimuth angle of the surrounding formations. Using information from the receiver output, the angles of the transmitter vector $\overline{M}_T$, i.e., ϕ_T and θ_T, are adjusted such that the transmitter vector tends to become perpendicular to the bedding plane of the surrounding formations. When this condition occurs, a substantial null is expected at the receiver output. This follows from the recognition that virtually no signal is induced between two perpendicular induction coils if one of the coils is aligned with the formation bedding plane. The transmitter tilt and azumuthal angles which yield a substantially null condition at the receiver output can therefore be recorded as a measure of the formation dip and dip azimuth angles at the given formation depth level.

To obtain a further understanding of the techniques to be employed, consider FIG. 3 wherein a transmitter vector $\overline{M}_T$ is shown as being oriented at a tilt angle ϕ_T and an azimuthal angle θ_T. The circle C_R (in dotted line) represents the plane of rotation of the receiver vector $\overline{M}_R$, the plane in which the circle lies is perpendicular to the transmitter vector as described above. The circle C_F (in dashed line) represents the formation bedding plane having a dip and dip azimuth that are to be determined. The circle C_H (in solid line) represents the horizontal plane; i.e., the x, y plane in the present coordinate system. The intersection of circles C_F and C_H is the line NN′ which is perpendicular to the dip azimuth of the formation bedding. The intersection between the circles C_R and C_H is a line MM′. At a given arbitrary transmitter orientation, MM′ will be different than NN′. The technique of the invention strives to bring MM′ into coincidence with NN′ (i.e., to adjust θ_T to obtain coincidence of azimuth) and then to tilt the receiver circle C_R until it coincides with C_F (i.e., to adjust ϕ_T to obtain coincidence of dip). This is done by appropriately adjusting the direction of the transmitter vector $\overline{M}_T$ as a function of the observed receiver output signal.

A measuring sequence in accordance with an embodiment of the invention is as follows: Initially, the transmitter is energized in such a way that $\overline{M}_T$ is oriented along the z axis (see FIG. 4). In terms of the coil systems of FIG. 1, this means that only the horizontal transmitter coil T_z is energized. The effective receiver coil sensitivities are initially adjusted (by adjusting their associated amplifiers, as will be described) so as to effectively place the receiver circle C_R in the horizontal plane; i.e., with the receiver vector $\overline{M}_R$ rotating in the x, y plane at an angular frequency ω. This situation is illustrated in FIG. 4 where the receiver circle is again represented by C_R. In terms of the FIG. 1 system, this would mean that only the signals from the coils R_x and R_y would contribute to the receiver output signal. The stated transmitter starting condition means that the value of transmitter tilt angle ϕ_T is initialized at zero, so that $\sin\phi_T = 0$ and $\cos\phi_T = 1$. The starting value of the transmitter azimuthal angle ϕ_T is arbitrarily initialized at zero, so $\sin\theta_T = 0$ and $\cos\theta_T = 1$. It follows from equation (2) that the receiver vector $\overline{M}_R$ for the starting conditions can be expressed as

$$\overline{M}_R = M_R(\overline{i}\cos\omega t - \overline{j}\sin\omega t) \quad (3)$$

It is seen that for the starting conditions, the receiver vector $\overline{M}_R$ will be aligned with the x axis at a reference time $t = 0$.

For the stated starting conditions, if a formation dip exists relative to the z axis, and if the formation has significant anisotropy, then the receiver will produce an output that varies in amplitude as a function of the receiver vector position. With the receiver vector rotating as a function of ωt, the receiver output will vary sinusoidally as a function of time, t. Nulls of the receiver output will occur at the times when $\overline{M}_R$ intersects the formation bedding plane; i.e., at $t = t_2$ and $t = t_4$ in FIG. 4. The peaks of the receiver output will occur at the times when $\overline{M}_R$ is aligned with the dip azimuth of the formation; i.e., at $t = t_1$ and $t = t_3$. A typical receiver output for the starting condition is illustrated in FIG. 5. The amplitude

of the sinusoidal waveform of FIG. 5 is called the "dip error signal" designated ϕ_E. The dip error signal is an indication of the size of the angle by which the transmitter vector will ultimately have to be rotated from the z axis to make it perpendicular to the bedding plane circle C_F. The existence of a dip error signal, ϕ_E, under the starting conditions can be recorded, if desired, as evidence of the presence of dip and anisotropy. If the initial dip error signal is zero, it means that there may be insufficient anisotropy to allow measurement of dip. If the formation is otherwise known to be anisotropic, then the dip is the same as the orientation of the coordinate system of the measuring device (i.e., in the z direction in the present simplified case).

If the starting dip error signal, ϕ_E, is appreciable, the formation dip azimuth angle, θ_f (shown in FIG. 4), can be determined from the relative "phase" of the receiver output signal. This can be achieved by measuring the time between a known reference of the rotating receiver vector (e.g. at $t = 0$), and an appropriate peak or null of the receiver output signal. In the example of FIGS. 4 and 5, the time to be determined is t_1, which is the time it takes for the rotating receiver vector to travel from the x axis ($t = 0$) to the position of the formation dip azimuth projection. Then we have

$$\theta_f = \omega t_1. \tag{4}$$

It will be understood that depending upon the quadrant in which the formation dip azimuth is located, the appropriate time reference may be either t_1 or t_3. This possible ambiguity can be overcome by consistently using either the occurrence of positive peaks or negative peaks of the receiver output as a measurement time. In practise, if the time of a null (or zero-crossing) is instead measured, one can consistently use either positive-going zero-crossings or negative-going zero-crossings, and then subtract $\pi/2$; i.e., for example:

$$\theta_f = \omega t_2 - \pi/2. \tag{5}$$

When a value of θ_f has been determined, it can be utilized to obtain new values of $\sin\theta_T$ and $\cos\theta_T$. These values are fed to the transmitter so that the transmitter vector $\overline{M}_T$ will move in the formation dip azimuth direction as the next step is implemented; namely, an adjustment of the transmitter vector tilt angle. (The new values of $\sin\theta_T$ and $\cos\theta_T$ are also fed to the receiver so that the receiver vector $\overline{M}_R$ continues to "track" in a plane perpendicular to $\overline{M}_T$). The adjustment of the transmitter tilt angle is implemented as a function of the dip error signal. That is, ϕ_T (and $\sin\phi_T$ and $\cos\phi_T$) is increased in accordance with the measured dip error signal, ϕ_E. Any residual dip error signal subsequently measured can be used to adjust the value of ϕ_T until the dip error signal is reduced to zero or some acceptable minimum value. The final value of ϕ_T is adopted and recorded as the formation dip angle, ϕ_f, at the particular depth level.

Reference is now again made to FIG. 1 for a description of embodiment of circuitry utilized to implement the techniques just described. An osciliator 210 operates at a suitable induction logging frequency. The output of oscillator 210 is coupled to multiplying amplifiers 211, 212 and 213 which are respectively designated as the T_x amplifier, the T_y amplifier, and the T_z amplifier. The output of amplifier 211 is coupled to transmitter coil T_x, the output of amplifier 212 is coupled to transmitter coil T_y, and the output of amplifier 213 is coupled to coil T_z. Amplifier 211 receives at its multiplier inputs signals proportional to $\cos\theta_T$ and $\sin\phi_T$. Amplifier 212 receives at its multiplier inputs two signals respectively proportional to $\sin\theta_T$ and $\sin\phi_T$. Amplifier 213 receives at its multiplier input a signal proportional to $\cos\phi_T$. (The source of these and other signals will be treated hereinbelow). It is seen that the outputs of the amplifiers 211, 212 and 213 are respectively the outputs required by Table I for steering the transmitter effective magnetic moment in accordance with equation (1) to a direction defined by the angles θ_T and ϕ_t.

The receiver coil R_x is coupled to both a multiplying amplifier 221 and another multiplying amplifier 222. In the embodiment of FIG. 1, the amplifiers in the receiver circuitry are used to apply the appropriate amplification or sensitivity factors to "steer" the effective receiver moment direction. Amplifier 221 receives multiplying input signals proportional to $-\sin\omega t$ and $\sin\theta_T$. Amplifier 222 receives multiplying input signals proportional to $\cos\omega t$, $\cos\theta_T$, and $\cos\phi_T$. The receiver coil R_y is coupled to each of two multiplying amplifiers 223 and 224. Amplifier 223 receives multiplying input signals proportional to $\sin\omega t$ and $\cos\theta_T$. Amplifier 224 receives multiplying input signals proportional to $\cos\omega t$, $\sin\theta_T$, and $\cos\phi_T$. The receiver coil R_z is coupled to multiplying amplifier 225 which receives multiplying input signals proportional to $-\cos\omega t$ and $\sin\phi_T$. The negative signals are implemented by applying them to negative polarity input terminals of their respective amplifiers, or by providing inverters. The outputs of amplifiers 221 and 222 are coupled to the inputs of summing amplifier 226, and the outputs of amplifiers 223 and 224 are coupled to the inputs of summing amplifier 227. The outputs of summing amplifiers 226 and 227 are, in turn, coupled to the input of another summing amplifier 228 which receives as a further input the output of amplifier 225.

The output of summing circuit 228 is readily seen to be proportional to the receiver magnetic

these outputs are added together, they yield a receiver signal $\overline{B} \cdot \overline{M}_R$ where $\overline{B}$ is a vector representative of the induced magnetic field from the formations and $\overline{M}_R$ is a unit receiver vector rotating at an angular frequency ω in a plane perpendicular to the unit transmitter magnetic moment vector $\overline{M}_T$.

The output of summing amplifier 228 is coupled to a phase detector 230. The other input to detector 230 is a reference signal at the induction logging frequency derived from oscillator 210. Detector 230 removes the induction logging frequency and generates a receiver output signal of the type illustrated in FIG. 5. The output of detector 230 is coupled to another detector 240 which receives as its second input a signal at angular frequency ω, this signal being derived from an oscillator 245. Recalling from FIG. 5 that the receiver output signal varies sinusoidally as a function of ω, it can be understood that the output of detector 240 will be a positive or negative D.C. signal representative of the dip error signal, ϕ_E.

The output of oscillator 245 is also coupled to a sin, cos generator 246 that is operative to generate the signals $\sin\omega t$ and $\cos\omega t$. These signals are also utilized in already-described portions of the receiver circuitry to obtain the desired rotation of the receiver vector $\overline{M}_R$ in the plane parallel to the transmitter vector.

The output of detector 230 is also coupled to a zero-crossing detector 250 which is operative to produce an output signal upon the occurrence of each positive-going zero-crossing in the receiver output signal. This output from the zero-crossing detector is coupled to a timing circuit 260 which receives as its other input a signal from a reference detector 265. The reference detector, in turn, receives the signals representative of $\sin\omega t$ and $\cos\omega t$ which are available from generator 246. The reference detector is operative to produce an output whenever both $\sin\omega t = 0$ and $\cos\omega t = 1$. This condition occurs at the time $t = 0$; i.e., the time when the rotating receiver vector is aligned with the x axis. The timer 260, which may comprise an analog ramp circuit, is reset to zero by the output of reference detector 265 and produces an output whose magnitude is representative of the time elapsed until the next positive-going zero-crossing. This time, designated t_n (and which will be, for example t_1 in FIGS. 4 and 5), is related to the formation dip azimuth angle θ_f in accordance with $\theta_f = \omega t_n - \pi/2$.

The output of timing circuit 260 is coupled via contact 1 of a relay section 300B to a holding circuit 270. The output of holding circuit 270 is coupled to sin, cos generator 275 that generates signals designated $\sin\theta'$ and $\cos\theta'$. The output of detector 240 is coupled, via contact 2 of a relay section 300A, to an analog-to-digital converter 280 having two outputs, 280A and 280B, that are coupled to up-down counter 281. Positive inputs to A/D converter 280 are output as digital signals on line 280A which causes counter 281 to count up, while negative inputs to A/D converter are output as digital signals on line 280B which causes counter 281 to count down the counter 281 is coupled, via D/A converter 282, to a sin, cos generator 285. The outputs of sin, cos generator 285 are respectively designated $\sin\phi'$ and $\cos\phi'$.

The outputs designated $\sin\phi'$ and $\cos\phi'$ are respectively coupled to contacts 2 of the relay sections 300C and 300D. The outputs designated $\sin\theta'$ and $\cos\theta'$ are respectively coupled to contact 2 of the relay sections 300E and 300F. Contact 1 of relay sections 300C, 300D, 300E, and 300F are respectively coupled to signals at respective levels of zero ($\sin\phi_T = 0$), unity ($\cos\phi_T = 1$), zero ($\sin\theta_T = 0$), and unity ($\cos\theta_T = 1$). The wiper contacts of relay sections 300C, 300D, 300E and 300F are coupled, as $\sin\phi_T$, $\cos\phi_T$, $\sin\theta_T$ and $\cos\theta_T$, respectively, to the appropriate inputs of the transmitter multiplying amplifiers 211—213 and receiver multiplying amplifiers 221—225. The outputs $\sin\omega t$ and $\cos\omega t$ of generator 246 are also coupled to the appropriate inputs of these multiplying amplifiers. The relay sections 300A, 300B, ... 300F are under common control, from the earth's surface, as indicated by dashed line 300X.

In the present embodiment, both signals from relay section 300A, the input to holding circuit 270, and the output of counter 281 are transmitted to the surface of the earth via armored multiconductor cable 15. Compass and inclinometer information will also typically be transmitted to the earth's surface. Further, the signals $\cos\phi_T$, $\sin\phi_T$, $\cos\theta_T$ and $\sin\theta_T$ may optionally be sent to the surface. At the earth's surface the signals tranmitted from downhole are recorded by recorder 350 as a function of borehole depth. The recorder 350 is conventionally provided with means (not shown) synchronized with the length of cable 15 and, accordingly, with the depth of the downhole logging device.

During a "mode 1" operation, each relay stage wiper is connected to contact 1, and this can be seen to result in the starting condition described in conjunction with FIG. 4. In particular, fixed values of $\sin\phi_T$, $\cos\phi_T$, $\sin\theta_T$ and $\cos\theta_T$ are used to steer the transmitter vector $\overline{M}_T$ in the z direction and establish an initial azimuth reference along the z axis. In this condition θ_f is determined at timing circuit 260 (contact 1 of relay section 300B) and recorded. Also, the dip error signal ϕ_E in mode 1 (contact 1 of relay section 300A) is recorded as indicative of the presence of anisotropy. Mode 2 operation can then be implemented (either manually or automatically) by switching each relay stage wiper to contact 2. Now, the values of $\sin\theta'$ and $\cos\theta'$, each derived from the receiver output during mode 1, are used as $\sin\theta_T$ and $\cos\theta_T$ to rotate the transmitter vector in the direction of the bedding plane dip azimuth. At the same time $\sin\phi'$ and $\cos\phi'$ are operative to rotate the transmitter tilt angle, as necessary, toward the normal to the bedding plane. It can be seen that any tilt error will be manifested as a dip error signal ϕ_E (output of detector 240) which will cause the count in counter 281 to be adjusted up or down. This, in turn, will cause adjustment of $\sin\phi'$ and $\cos\phi'$ that will reduce the dip error signal. The feedback arrangement

results in a counter output that represents ϕ_f. At this point the dip error signal ϕ_E should approach zero. At the next depth level, if no severe formation dip change has occurred, the counter 281 will not have to be modified very much, so the time for stabilization of the feedback process will be shorter than if, say, the counter 281 was always initialized at some fixed value.

The invention has been described with reference to a particular embodiment, but variations within the spirit and scope of the invention will occur to those skilled in the art. For example, it will be understood that if no significant receiver signal is obtained during mode 1, the transmitter vector direction could be modified to obtain a receiver signal from which θ_f can be determined (assuming the formations are anisotropic). Also, it will be understood that a choice of digital, analog and/or manual techniques could be employed to implement or simulate the various circuit and/or operational functions hereof.

CLAIMS

1. A method of determining properties of subsurface formations surrounding a borehole, comprising the steps of: transmitting electromagnetic energy into said formations by individually energizing transmitter coils in a transmitter coil array and

electronically steering the direction of the magnetic moment resulting from the magnetic field components generated by said transmitter coils; and

processing signals detected in receiver coils of a receiver coil array to derive said properties.

2. The method as defined in claim 1, including the steps of: individually sensing the signals induced in said receiver coils; and

controlling the relative sensitivities associated with each of said receiver coils to steer the effective sensing direction of the receiver coil array.

3. The method as defined in claim 2, including:

a) rotating the effective sensing direction in a plane substantially perpendicular to the direction of said magnetic moment;

b) detecting the receiver coil array output;

c) varying the magnetic moment direction as a function of the receiver coil array output; and

d) repeating steps (a), (b), and (c) until the magnetic moment direction is substantially perpendicular to the formation bedding plane.

4. The method as defined by any one of claims 1 to 3, wherein the azimuthal direction of the magnetic moment is varied as a function of the phase of the receiver coil array output.

5. The method as defined by any one of claims 1 to 4, wherein the tilt angle of the magnetic moment is varied as a function of the peak magnitude of the receiver coil array output.

6. Apparatus for determining properties of subsurface formations surrounding a borehole, comprising:

an array of transmitter coils;

an array of receiver coils;

means for individually energizing said transmitter coils;

electronic transmitter steering means for controlling said energizing means to electronically steer the direction of the magnetic moment resulting from the magnetic field components generated by said transmitter coils; and

receiver processing means for processing the signals induced in said receiver coils.

7. Apparatus as defined by claim 6, wherein said electronic transmitter steering means is operative to steer the direction of the transmitter magnetic moment in three dimensions.

8. Apparatus as defined in claim 6 or claim 7, wherein said receiver processing means includes:

means for individually sensing the signals induced in said receiver coils and for combining the sensed signals; and

electronic receiver steering means for controlling the relative sensitivities of said individual sensing means to steer the effective sensing direction of the receiver processing means.

9. Apparatus as defined by claim 8, wherein said electronic receiver steering means is operative to steer the effective sensing direction of the receiver processing means in three dimensions.

10. Apparatus as defined by claim 8 or claim 9, wherein said electronic receiver steering means is coordinated with said electronic transmitter steering means and is operative to steer the effective sensing direction of said receiver processing means in a direction substantially perpendicular to the direction of the transmitter magnetic moment.

11. Apparatus as defined by claim 10, wherein said electronic receiver steering means is operative to rotate the effective sensing direction of said receiver processing means in a plane substantially perpendicular to the direction of the transmitter magnetic moment.

12. Apparatus as defined by claim 11, wherein said receiver processing means is operative to generate a receiver signal having an amplitude and phase which are functions of the angular differences between the plane of said rotating effective sensing direction and the plane of the surrounding formation bed.

... defined by claim 12, wherein said receiver processing means includes means

direction perpendicular to the plane of the surrounding formation bed.

14. Apparatus as defined by any one of claims 6 to 13, wherein said transmitter coil array includes first, second, and third transmitter coils having mutually orthogonal axes and said receiver coil array includes first, second, and third receiver coils having mutually orthogonal axes.

15. Apparatus as defined by claim 12, wherein said receiver processing means is operative to vary the tilt angle of said magnetic moment as a function of the peak amplitude of said receiver signal.

16. Apparatus as defined by claim 12 or claim 15, wherein said receiver processing means is operative to vary the azimuthal direction of said magnetic moment as a function of the phase of the receiver signal.

17. A method of determining properties of subsurface formations surrounding a borehole, the method being substantially as herein described with reference to the accompanying drawings.

18. Apparatus for determining properties of subsurface formations surrounding a borehole, the apparatus being substantially as herein described with reference to the accompanying drawings.

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